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# Tunable polarisation-maintaining filter based on liquid crystal photonic bandgap fibre

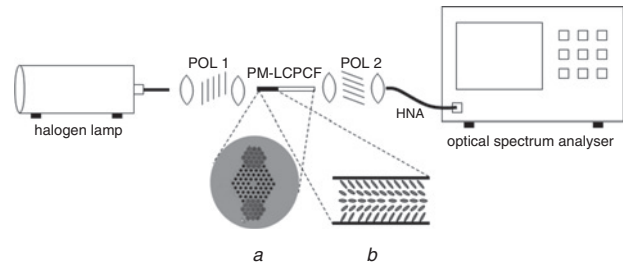
L. Scolari, C.B. Olausson, J. Weirich, D. Turchinovich, T.T. Alkeskjold, A. Bjarklev and L. Eskildsen

A tunable and polarisation-maintaining all-in-fibre filter based on a liquid crystal photonic bandgap fibre is demonstrated. Its polarisation extinction ratio reaches 14 dB at 1550 nm wavelength. Its spectral tunability range spans over 250 nm in the temperature range 30–70°C. The measured transmission spectrum is compared with that obtained through finite element simulations.

**Introduction:** Photonic crystal fibres (PCFs) present the unique characteristic of having microholes running along their length. They can be infiltrated with liquid materials, which can allow manipulation of their optical properties. Solid core PCFs guide light by modified total internal reflection [1]. If their microholes are filled with a liquid having a refractive index higher than the constituent material of the fibre, antiresonances of the high-index rods give rise to discrete photonic bandgaps where the light is confined to the core [2]. In particular, among liquid materials, liquid crystals (LCs) are attractive because they exhibit very high thermo-optic and electro-optic effects, leading to the possibility of realising tunable components [3]. All-in-fibre tunable devices such as spectral filters, switches, polarisation controllers and polarimeters have been fabricated using this technique and their tunability has been achieved thermally, electrically or optically [3–5]. Birefringence tunability has also been demonstrated in highly birefringent PCF filled with LCs [6]. Moreover, the bandwidth of the transmission bands can be narrowed, and their shape tailored by tapering or inflating the microholes [7]. This leads to the possibility of fabricating all-in-fibre band-pass, notch, highpass or lowpass filters with a tunable operating wavelength and a tunable bandwidth, representing a strong alternative to bulk optics filters, which are susceptible to misalignment. All-in-fibre devices are fully compatible with existing fibre technology and can be adjusted to the specific network to optimise its performance. In this Letter, a polarisation-maintaining (PM) filter based on a 30 cm PCF filled with 1.2 cm LC is demonstrated and its transmission spectrum is simulated using a finite element code. A polarisation extinction ratio (PER) of 14 dB at 1550 nm is obtained experimentally. The PM filter is thermally tunable and a 250 nm-wide spectral shift of the bandgaps is achieved by tuning the filter from 30 to 70°C. Such a device can, for example, be used in modelocked fibre lasers to perform spectral shaping and intra- and extracavity dispersion management. A high PER of all the elements used in fibre lasers is, in fact, crucial for the laser stability.

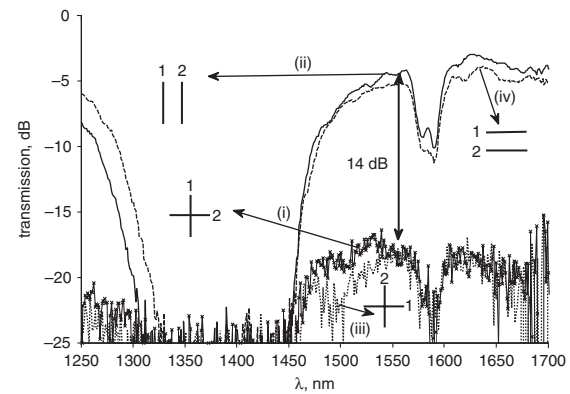
**Setup, discussion and results:** The fibre used in this experiment is a large mode-area PM fibre with a core size of 15  $\mu\text{m}$  (LMA-PM-15) from Crystal Fibre A/S, Denmark. A cross-section of the fibre is shown in the inset *a* of Fig. 1. The hole size  $d$  is 4.7  $\mu\text{m}$  and the inter-hole distance  $\Lambda$  is 9.8  $\mu\text{m}$ . Boron rods are inserted on opposite sides of the core at the preform stage in order to obtain stress-induced birefringence that facilitates the PM properties of the fibre. LMA-PM-15 has a birefringence  $\geq 8 \times 10^{-5}$  in the spectral range 900–1700 nm and a PER of  $\geq 20$  dB at 1550 nm. A LC called MDA-00-3969 from Merck, Germany, is infiltrated by capillary forces in the PCF for 1.2 cm in order to induce a filtering effect in the fibre. MDA-00-3969 has an ordinary and extraordinary index of 1.4978 and 1.7192 (measured at 589.3 nm and 20°C), respectively. Polarisation optical microscopy studies of this LC infiltrated in a 5  $\mu\text{m}$  silica capillary show that the alignment is splayed, with a 45° angle to the boundaries, as illustrated in inset *b* of Fig. 1. The PER measurement at room temperature is performed by positioning the LCPCF device between two polarisers. Lenses with a magnification of 20 $\times$  and an NA of 0.5 are used to couple white light from a halogen lamp into the LCPCF, as illustrated in the setup of Fig. 1. The light is collected by an optical spectrum analyser through a high numerical aperture (HNA) optical fibre. The first polariser is aligned along the slow or the fast axis of the fibre. The second polariser is added, and the two polarisers are iteratively rotated to minimise the transmission in the bandgaps. The resulting spectrum is recorded and corresponds to curve (i) in Fig. 2. The second polariser is then rotated 90°, such that it will be co-aligned with polariser 1. The corresponding transmission spectrum is shown in

curve (ii) of Fig. 2). The polarisation extinction ratio is the ratio between the power measured in these two cases – the polarisers in-line and the polarisers crossed – in dB units. To verify that polariser 1 is in fact aligned along one of the two PM axes, polariser 1 is rotated 90° and the same measurements as above are repeated (curves (iii) and (iv)). The transmission spectra for these two cases are expected to be the same if polariser 1 is aligned along one of the two PM axes. In Fig. 2 we notice a small difference between them; we expect this is caused by the LC alignment which does not have a perfect cylindrical symmetry in the holes of the fibre. A PER of 14 dB is measured at 1550 nm and a PER of 17 dB is measured at 1200 nm.

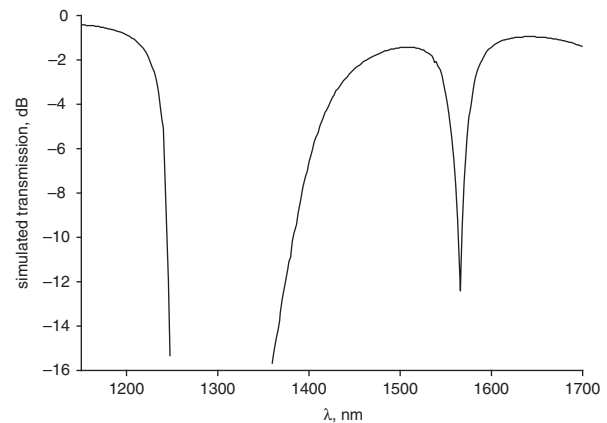


**Fig. 1** Schematic of setup

Inset: *a* Micrograph of fibre used in experiment (LMA-PM-15)  
Inset: *b* Alignment of LC infiltrated in fibre



**Fig. 2** Normalised transmission spectrum of LCPCF measured with crossed (minimum transmission) and inline polarisers (maximum transmission) at room temperature

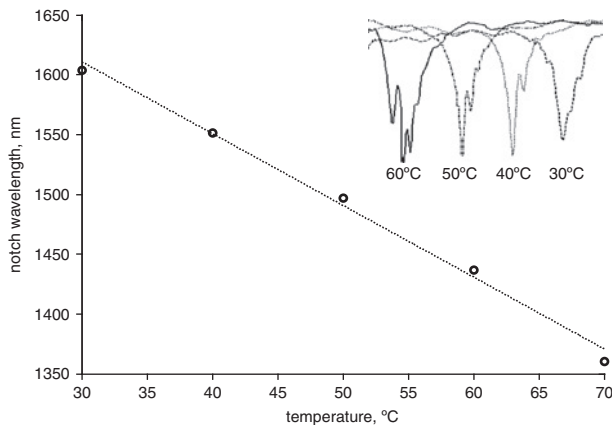


**Fig. 3** Simulated transmission spectrum of LCPCF at room temperature

Finite element simulations are also carried out in order to obtain the room-temperature transmission spectrum of the LCPCF and compare it with the experimental one. The modelling tool used can solve structures exhibiting arbitrary dielectric tensors, and is therefore particularly appropriate for the study of this LCPCF device, where the LC used has a splayed alignment with all nine components of the  $\epsilon$  tensor nonzero. Coupling losses generated from the mismatch of TIR core mode and the PBG core mode are calculated and added to the simulated confinement losses. Reasonable agreement is observed between our measurements and simulations (shown in Fig. 3). However, a shift of 20 nm compared to the

measurements is observed for the notch in the 1450–1700 nm bandgap and a shift of 50 nm is observed for the bandgap at lower wavelengths. This difference is due to varying hole size of the fibre used in the experiments compared to the ideal simulated one. Moreover, the refractive indices of MDA-00-3969 are measured with an Abbe interferometer at visible wavelengths and extrapolated to the near-infrared, using Cauchy parameters.

The thermal tunability of the PM LCPCF filter is investigated by positioning the LC filled section on a thermal plate. A standard SMF connected to a white light source is butt-coupled to the filter and the transmission spectrum is measured using an optical spectrum analyser. The temperature of the thermal plate is varied from 30 to 70°C and the transmission spectrum recorded every 10°C. Fig. 4 shows the wavelength of the notch against temperature. A tunability range of 250 nm is achieved in this temperature range. The shift of the bandgaps against temperature is almost linear. By choosing a different LC, the bandgaps can be shifted to specific wavelengths required by the specific application. In the case of an all-PM modelocked fibre laser, the tunable PM filter can be used for spectral shaping in the cavity, ASE filtering in the amplifiers, and for tunable dispersion control both inside and outside the cavity, thus allowing for monolithic tunable pulse shaping.



**Fig. 4** Temperature tunability of notch spectral position of PM-LCPCF  
Inset: Corresponding spectra around notch region at different temperatures

**Conclusions:** An all-in-fibre PM filter has been demonstrated by infiltrating a PM PCF with LC. The PCF has two boron rods on each side of the core and maintains the polarisation with a PER of 20 dB at

1550 nm. By infiltrating this fibre with a LC, bandgaps are achieved in the transmission spectrum. A PER of 14 dB at 1550 nm is measured, opening up the possibility of using this device as a polarisation-maintaining filter, e.g. in the fabrication of fibre lasers. Tunability has also been explored and a wavelength shift of 250 nm has been measured in the temperature range 30–70°C.

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